System and Power Module Requirements for Commercial, Construction & Agriculture Vehicles CAV

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Never stop thinking

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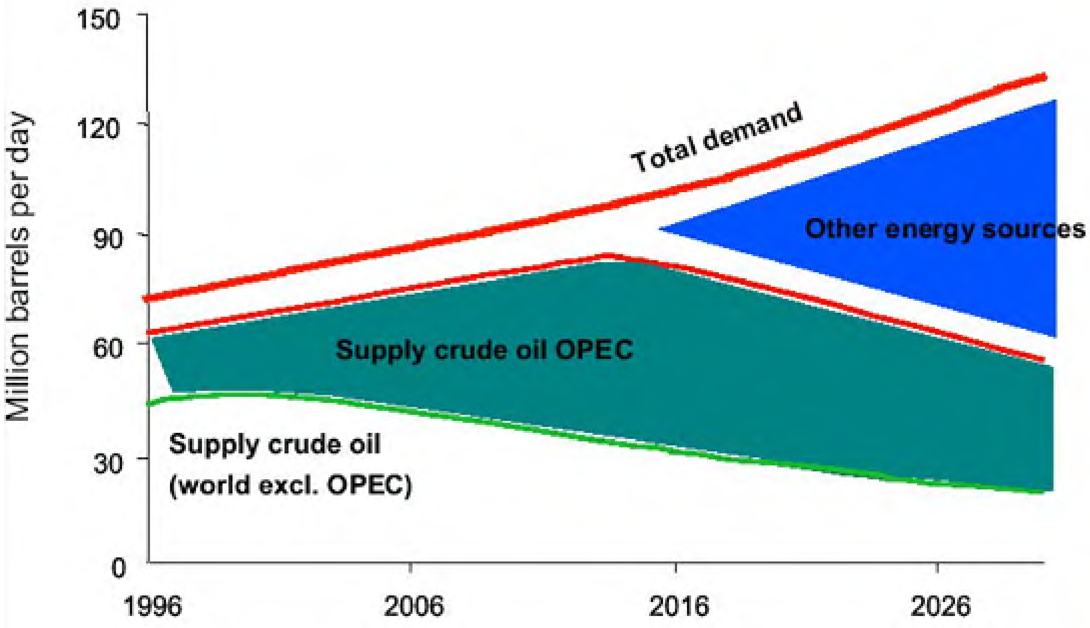
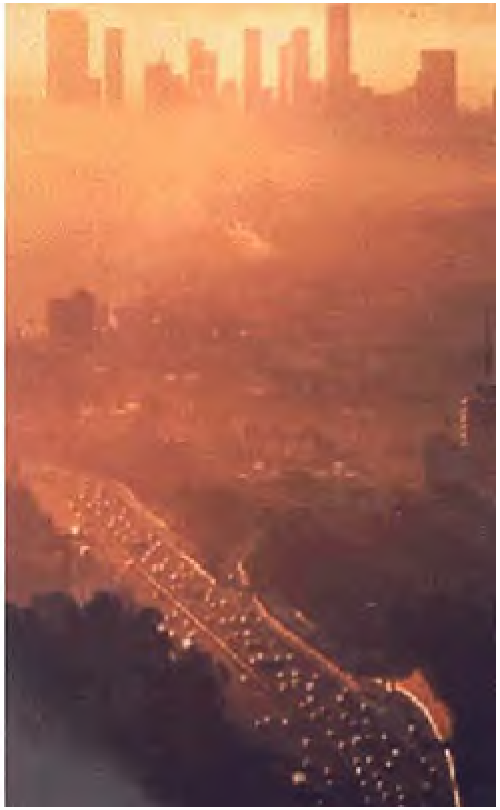
Motivation for electrification of CAV's

Source: EPE2007, Tutorial on 'Propulsion systems for hybrid and fuel cell electric vehicles' by Joeri Van Mierlo





Energy consumption and crude oil demand has accelerated over the last decade, increasing pollution and global warming. Electrification of vehicle propulsion drives improves the drive train efficiency and allows significant savings in fuel costs and CO_2 emissions. As the fuel consumption of CAV's is larger per vehicle compared to passenger cars, CAV hybridization will play a significant role in mitigating the effects of burning fossil fuels and produce a faster return on investment.

Application Examples

1l diesel -> 1,2€

Commercial applications:
Key driving forces are regulations

Source: www.isecorp.com

Yearly fuel consumption: 47300l (56,7k€)
20% saving results in 9460l (11,3k€)

Source: Hybrid Refuse Truck Feasibility Study

Yearly fuel consumption: 21000l (25,2k€)
25% saving results in 5250l (5k€)

Construction applications:
Key driving forces are fuel savings and mechanical construction

Source: articles.directorym.com

Fuel Consumption: 20 gal/1h ->182k€@2kh
25% saving results in 45,3k€ @2kh work

Source: Newsletter, LeTourneau,

L1150

Fuel Consumption: 47 gal/1h ->(853k€)@4kh
42% saving results in 360k€ @ 4kh work

Yearly fuel consumption:
2000l for 25 000km (2,4k€)
15% saving results in 300l ->
360€

There are probably more specific reasons for electrification programs in Commercial, Agriculture and Construction vehicles…

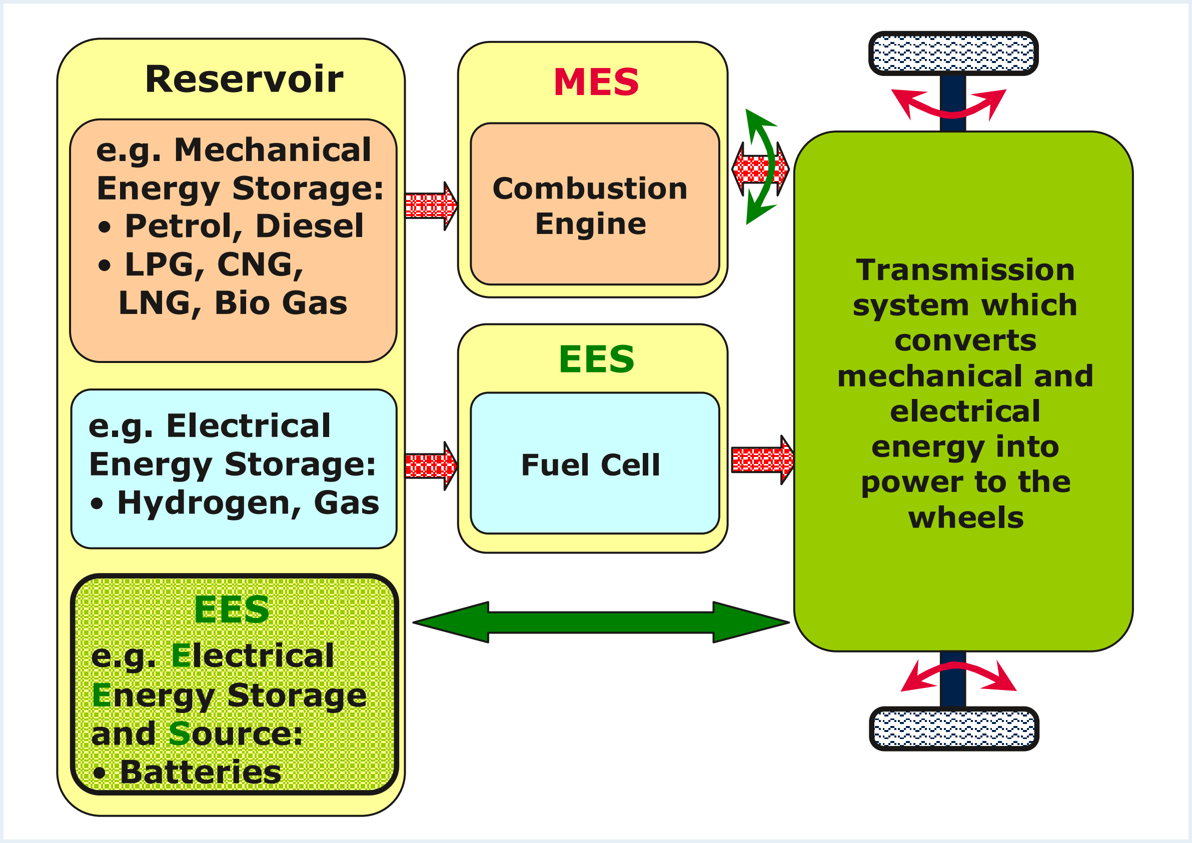
Hybrid Power Trains
General overview of Hybrid propulsion drives

Hybrid propulsion drives consist of four main components:

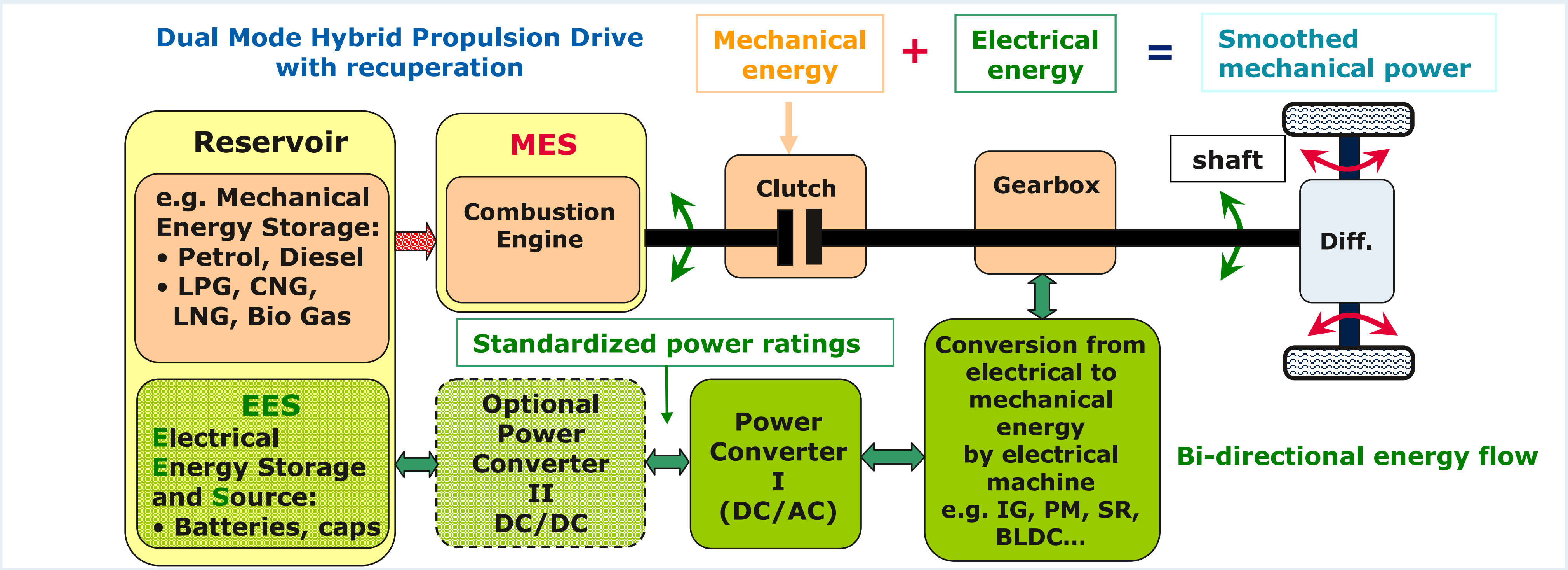
- Mechanical Energy Source (MES)
- Electrical Energy Source (EES)
- Energy storage for Mechanical and Electrical energy source (**Reservoir**)
- Transmission system which converts both energies into a motion which drives wheels

There are many possible power train topologies
but the two most common are:

- Series, where 100% of the power to the wheels is produced by an electric machine
- Parallel, where power to the wheels is taken mostly from the Mechanical Energy Source, and the Electrical Energy Source assists during acceleration and/or deceleration



Hybrid Power Train - example
Dual-Mode Hybrid Propulsion Drives - theory



Dual Mode Hybrid Propulsion Drive with recuperation

Mechanical energy + **Electrical energy** = **Smoothed mechanical power**

Reservoir

e.g. Mechanical Energy Storage:
- **Petrol, Diesel**
- **LPG, CNG, LNG, Bio Gas**

EES
Electrical Energy Storage and Source:
- **Batteries, caps**

MES

Combustion Engine

Clutch

Gearbox

shaft

Diff.

Standardized power ratings

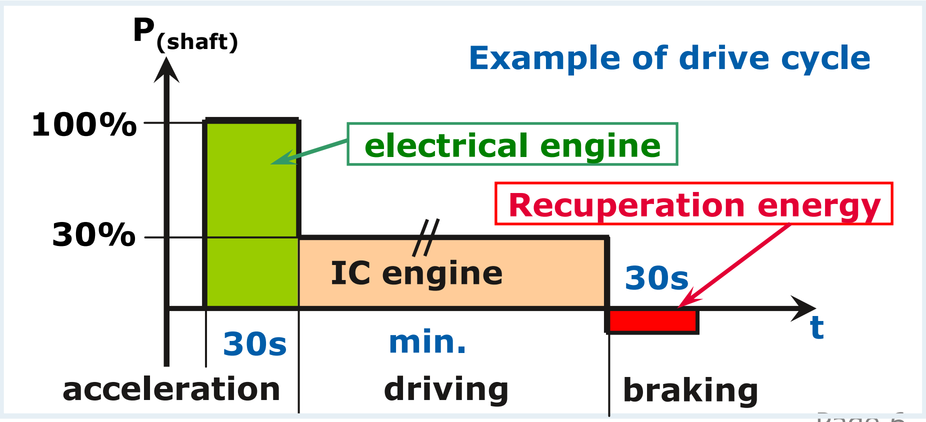
Optional Power Converter II DC/DC

Power Converter I (DC/AC)

Conversion from electrical to mechanical energy by electrical machine e.g. IG, PM, SR, BLDC…

Bi-directional energy flow

A dual-mode hybrid propulsion system can operate as a series or parallel power train dependent on the vehicle speed. The hybrid propulsion system operates in series mode (open clutch) when the vehicle starts from zero speed. After the vehicle reaches a certain speed, the combustion engine contributes to the shaft power. The battery of the ESS in this stage can be recharged.



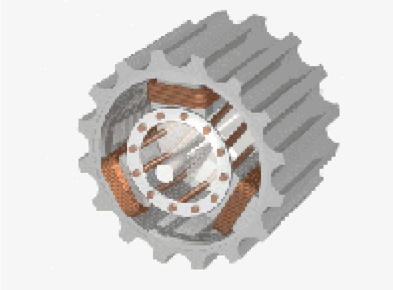
Hybrid Power Train
Hybrid Propulsion Drive - example

The LeTourneau hybrid loader utilizing traction drives, powered by Infineon Technologies AG IGBT modules and using a diesel engine as the Mechanical Energy Source.

Electric Motors
An overview

The parallel hybrid power train needs at least one electric machine which works as a generator during braking and as a motor during acceleration. The series hybrid power train utilizes a minimum of two electric machines, one operating predominantly as a generator and the second predominantly as a motor. The table below depicts the most popular electric motors used in Hybrid Power Trains.

	Generator	**Traction motor**
Machine type	▪ **Permanent Magnet (PM)** ▪ **Switched Reluctance (SR)** ▪ **Induction or Asynchronous Machine (IG)**	▪ **Induction or Asynchronous Machine (IM)** ▪ **Permanent Magnet (PM)** ▪ **Switched Reluctance (SR)** ▪ **Brushless Direct Current (BLDC) for small power e.g. e-bike**

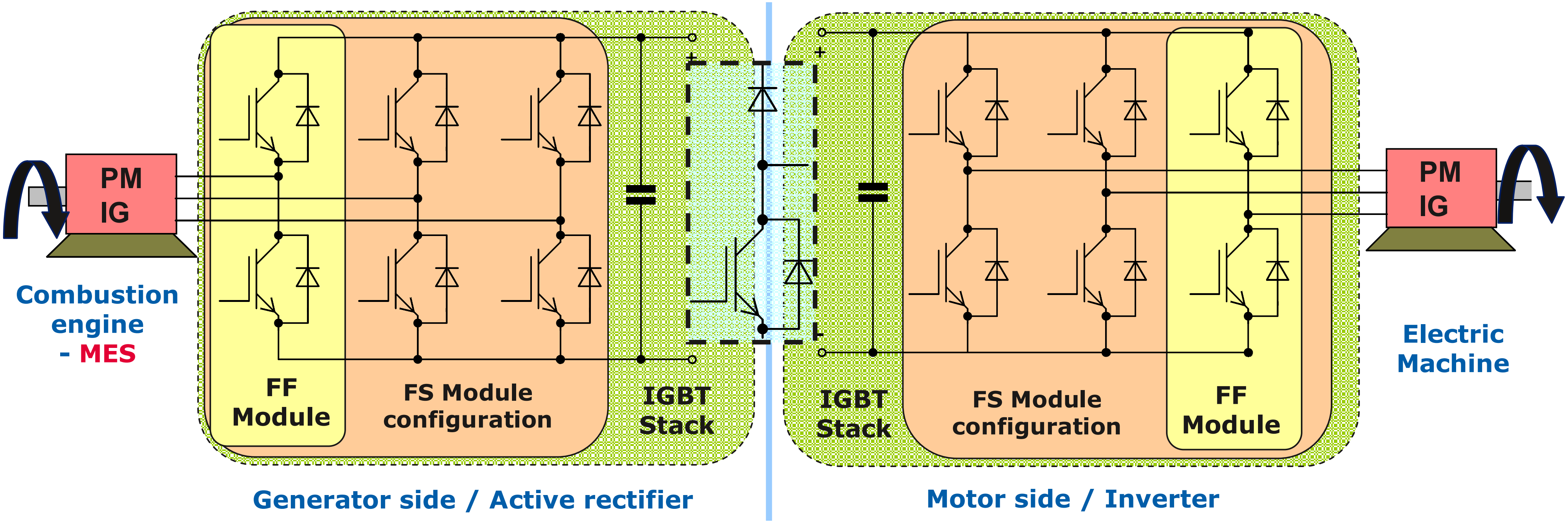


Induction Machine
Source: de.wikipedia.org

Parallel Power Train with PM machine
Source: IAA2008, Mitsubishi Fuso

SR Machine
Source: www.srdrives.com

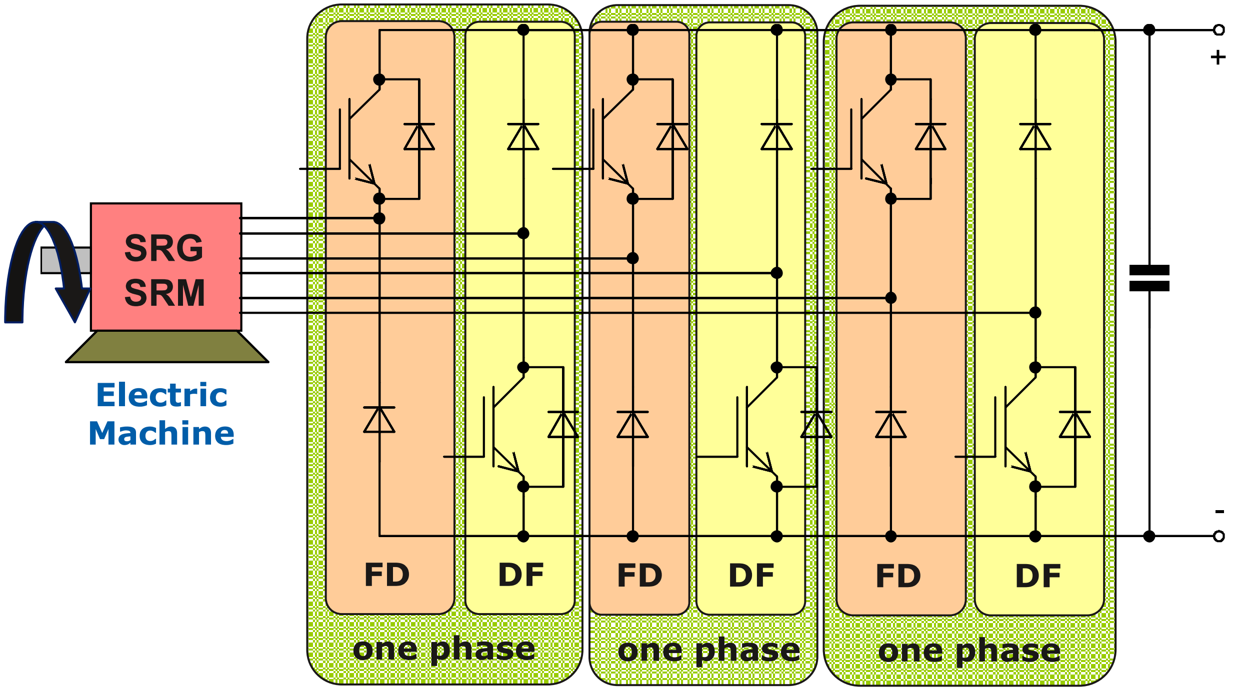
Converter Topologies – PM, IPM, IM, IG



The converter topologies for permanent magnet and induction machines on the generator and the motor side are typically identical – a 3-phase full bridge. Depending on the system configuration, the active rectifier can be replaced with rectifying diodes and a chopper to the DC-link when four quadrant system operation is not needed.

Regardless of e-machine types, the requirements for the semiconductor switches are the same.

Converter Topologies - SR



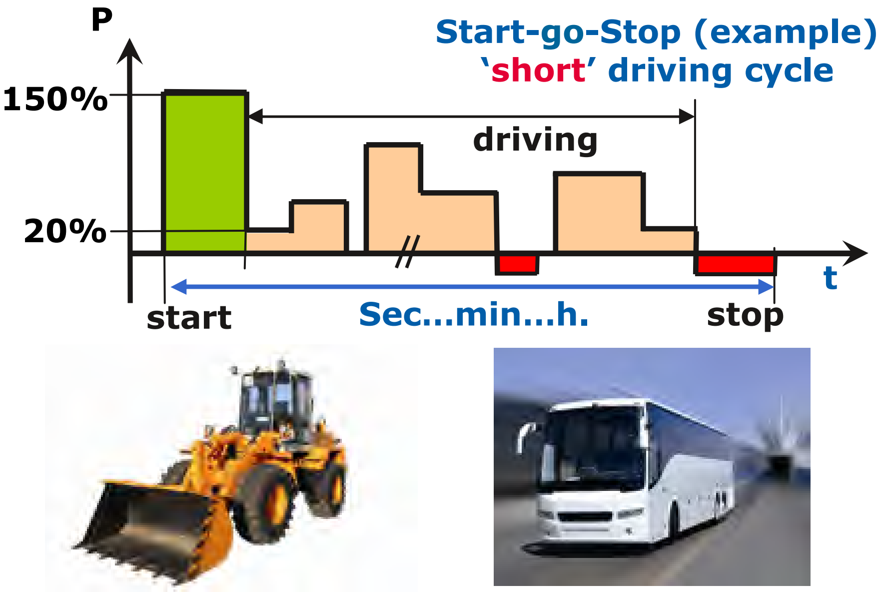
The typical Switched Reluctance motor/generator requires a three-phase converter configuration where each phase consists of two chopper modules (FD and DF). Due to a combination of regeneration and commutation strategy the size of the FWD diode needs to be larger than its complementary IGBT. The switching frequency is generally in the range of a few hundred Hz. In order to achieve the maximum efficiency, silicon with the lowest saturation voltage should be selected.

Reliability requirements of the semiconductor switches used in inverters dedicated to SR machines are similar to those used with PM or IM.

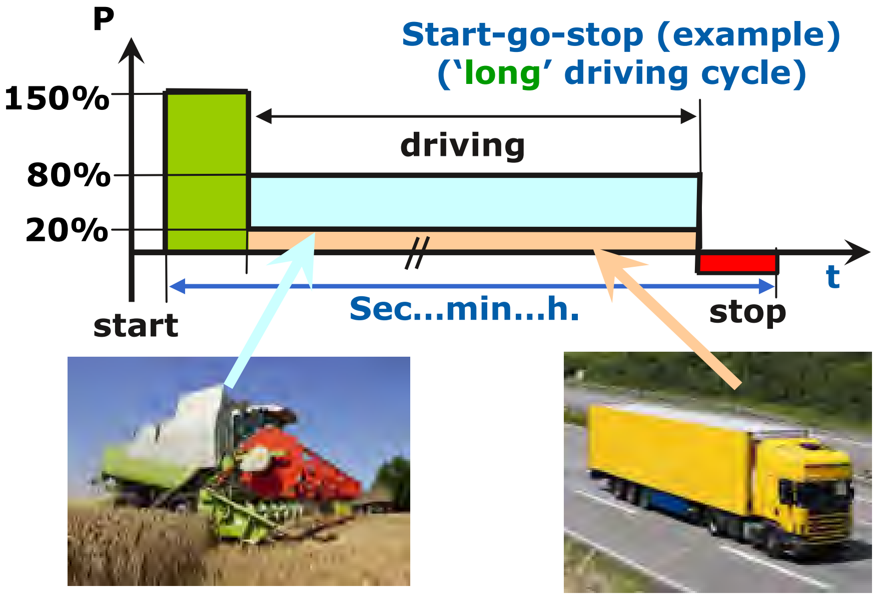
Semiconductor Module Requirements

There are two key factors in the selection of the appropriate power module:
- thermal: maximum junction temperature is a result of applied load and cooling conditions
- reliability: wear out mechanisms which determine module lifetime

Similarly designed converters, from the thermal point of view, can have different lifetimes depending on the load cycle and the electric machine. The load (drive) cycles in CAV's depend on the kind of vehicle and generally can be divided into two types:



- lots of small cycles with high amplitude
- frequent motoring/regenerating cycles
- parallel and series hybrid possible



- fewer small cycles with high amplitude
- stall condition for the e-machine can occur
- inverter power is 'stable' after the start
- parallel and series hybrid possible

Semiconductor Module Requirements

Regardless of the driving cycle or the electric machine type (IM, PM and SR), a suitable CAV inverter topology can be utilized. This results in the conclusion that all modules designed for hybrid propulsion drives should have similar reliability requirements. Due to complicated driving cycles, the most important parameters determining appropriate semiconductor module selection are: Thermal Cycling (TC), Power Cycling (PC) and vibration withstand capabilities.

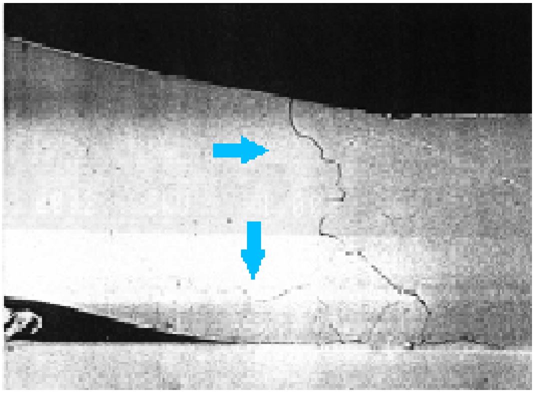
CAV oriented semiconductor module requirements:

Topology	**chopper, half-bridge, full bridge**
Blocking voltage class	**75-150V (MOS), 600-6500V (IGBT)**
Lifetime	**5 – 20 years, (8kh-60kh)**
Vibration	
Sweep sine	**≤15g (47Hz-2kHz), each axis**
Random	**≤15g (47Hz-2kHz), each axis**
Shock	**50g, each axis**
Thermal cycling (die and system solder)	
Passive (TST)	**N_{cycles}: application specific** **T=-40°C…150°C**
Active (internal heat)	**15k – 30k (2-6min, Δt=80°C)**
Power cycling (die bonds)	
@ Tjmax=150°C	**2e06 (Δt=40°C)**

Reliability of IGBT modules

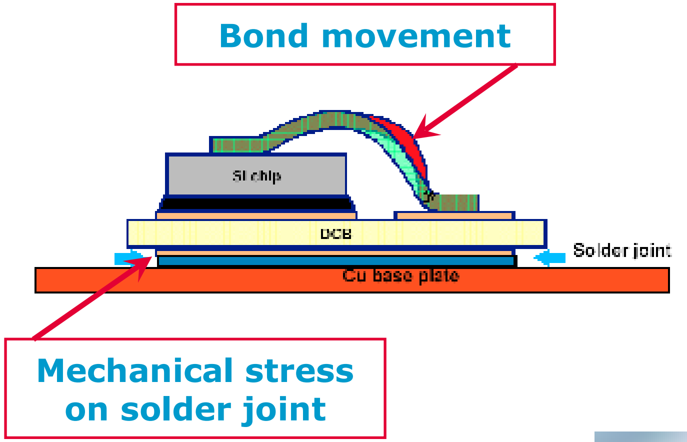
There are three key parameters which affect the long term reliability of power modules in CAV applications: Power Cycling (reliability of bond wire connections), Thermal Cycling (reliability of solder connections) and mechanic stability (vibration).

Power Cycling (bond wires)



Heel cracks

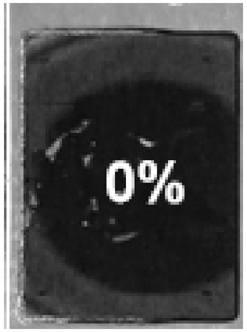
Bond lift-off



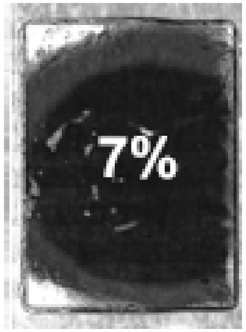
Bond movement

Mechanical stress on solder joint

Thermal Cycling (solder)

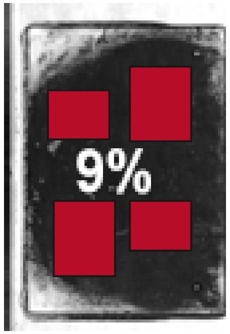


0 cycles



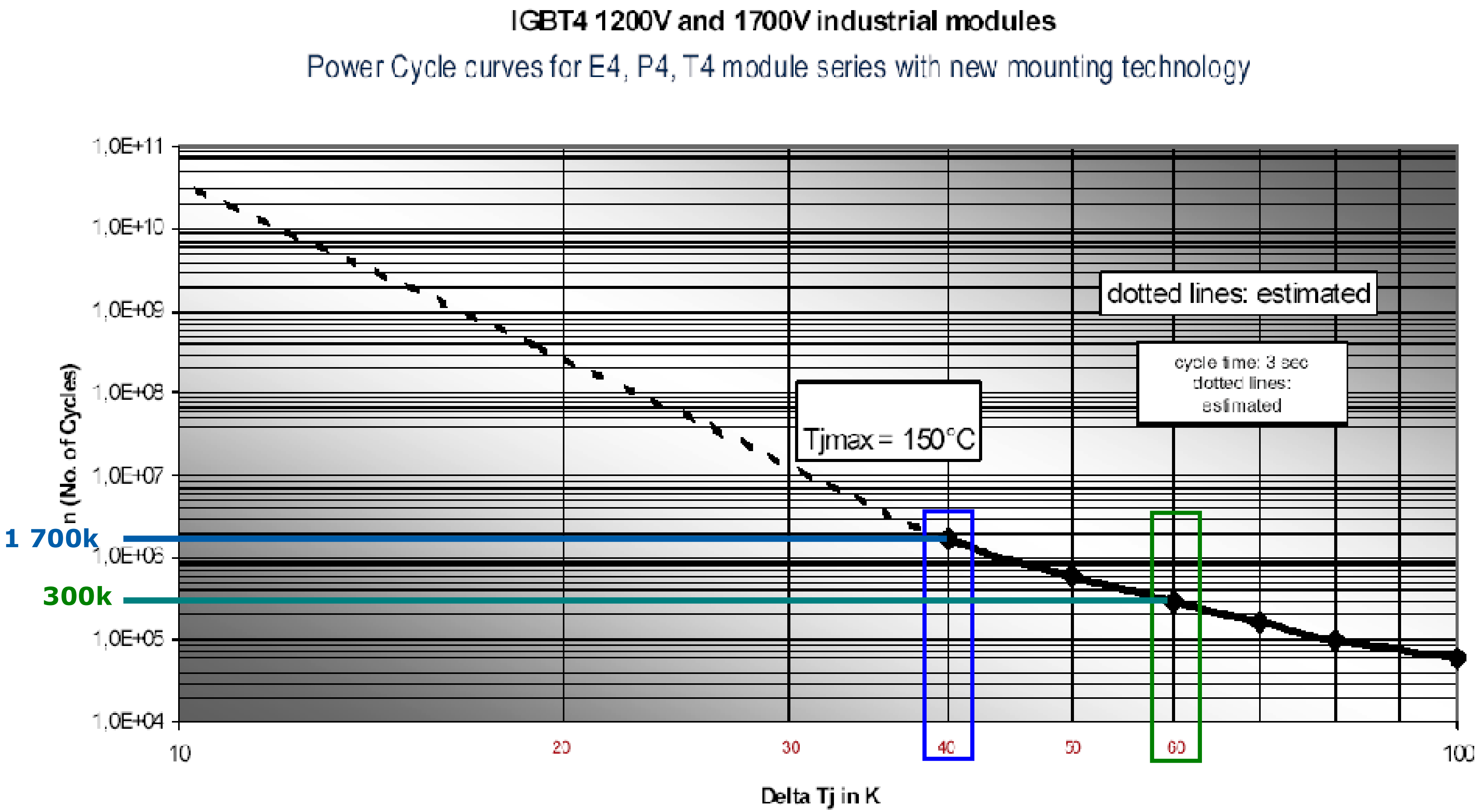
7k5 cycles

15k cycles



Solder delaminating where ΔT=80°C , T_{start}=25°C

Reliability of IGBT modules
Power Cycling – the curve

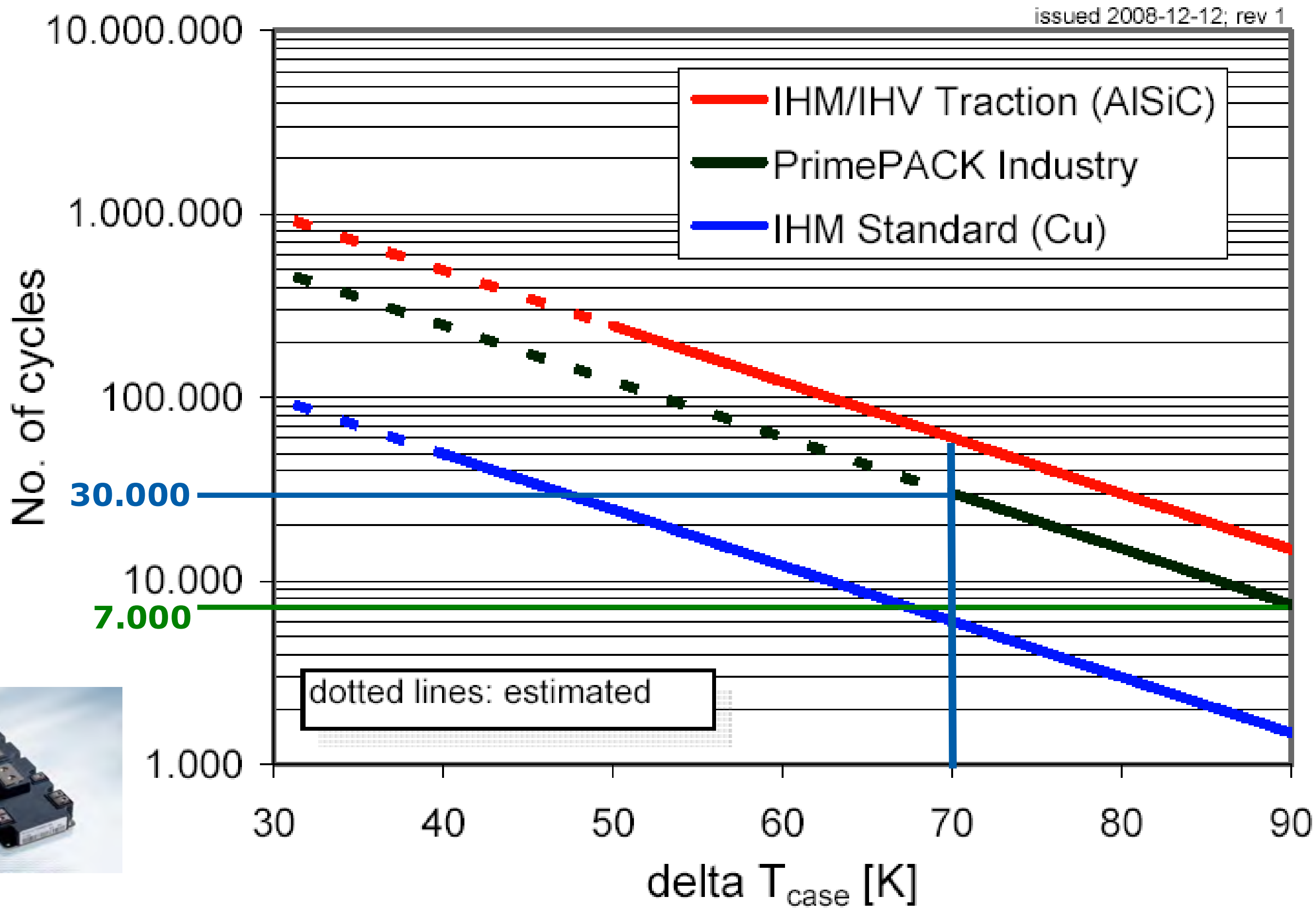


Number of cycles is dependent on the maximum temperature and the temperature swing. For example:

IGBT4	**1 700kc**	**@Tvjmax=150°C, ΔT=40°C (110°C – 150°C)**
IGBT4	**300kc**	**@Tvjmax=150°C, ΔT=60°C (90°C – 150°C)**

Reliability of IGBT modules
Thermal Cycling – the curve (PrimePACK™)

Thermal Cycling Capability for High Power Modules



cycle time:

$t_{on}+t_{off}$ typ. 5min

temperature level:

$T_{case,min}$=25°C

load conditions:

T-rise by internal active heating

T-fall by external cooling

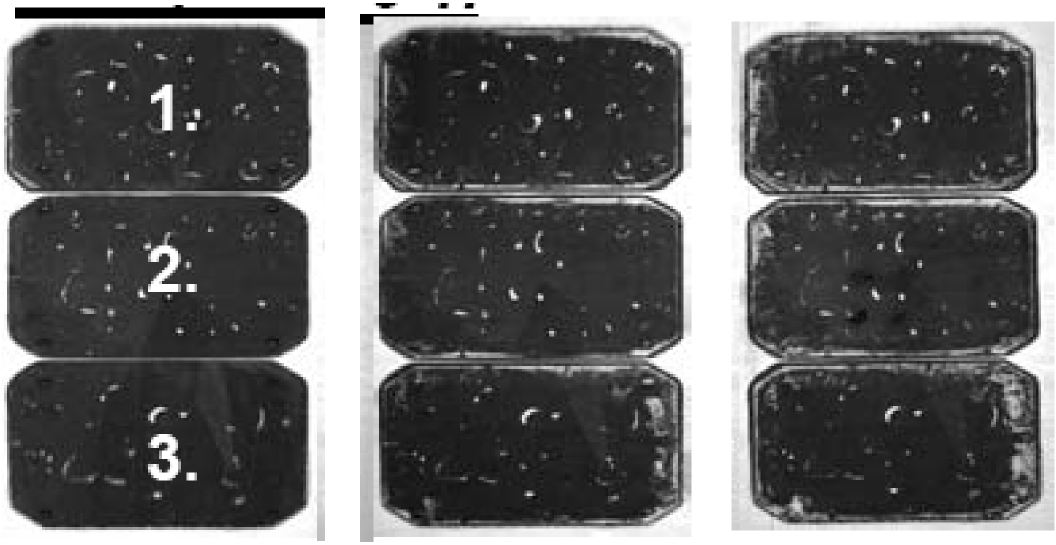
For a overall lifetime estimation the respective dependency N=f(ΔTvj) has also to be taken into account ("Power cycling curve")

Reliability of the solder layer depends on their temperature swing and starting temperature. For example:

30.000c @ΔT=70°C or 7.000c @ΔT=90°C

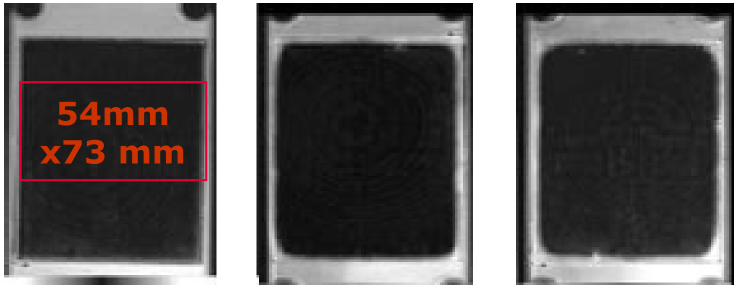
Reliability of IGBT modules
Thermal shock test – TST (part of TC)

The wear out mechanism on solder layers normally accelerates with increased cycle temperatures.



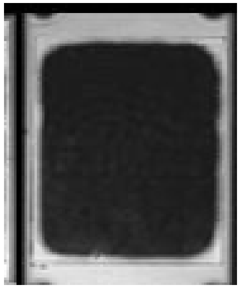
0c 500c 1000c

USM after Thermal Shock Tests @ temperature swing from -40°C to 150°C meaning ΔT=190°C achieved with HP1 module. Test PASSED!



0c 500c 1000c

2250c



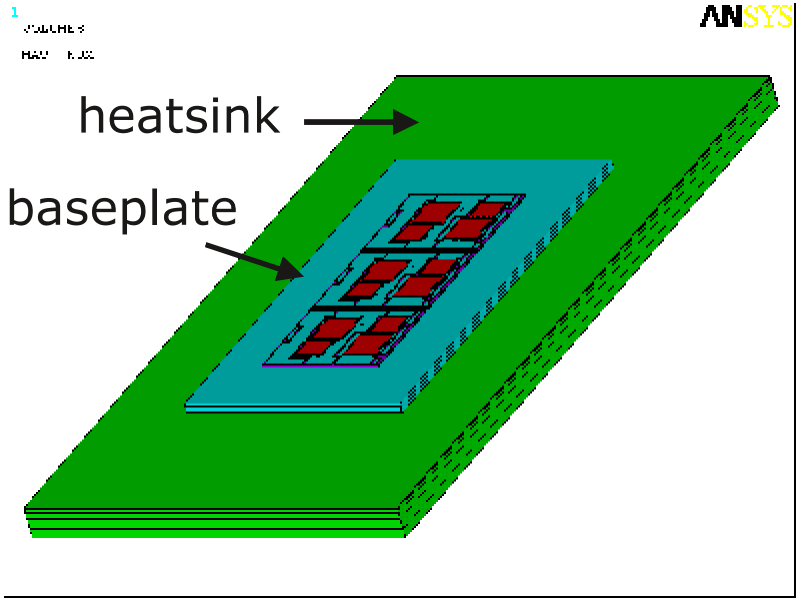
USM after Thermal Shock Tests @ temperature swing from -40°C to 150°C meaning ΔT=190°C achieved with new joining techniques for module with copper baseplate. Test PASSED!

Today's joining technologies allow an attachment of the DBC to it's copper baseplate without delamination problems even @ high temperature swings. This results in the long module lifetimes (even at large temperature gradients) required by CAV applications.

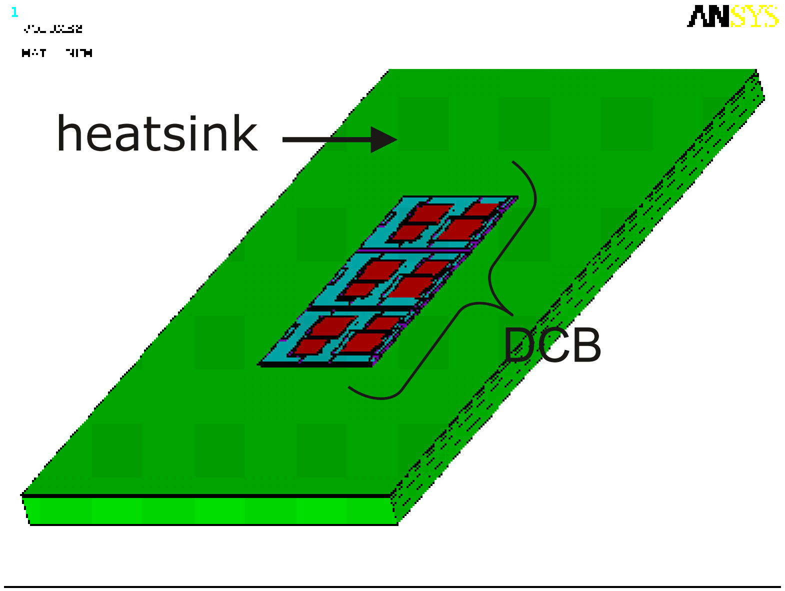
Why design a CAV module with a baseplate?

Regardless of technology, every isolated power module must meet the working conditions determined by load cycle and the thermal flow from junction to ambient. Thus, the key calculations to make are the junction and case temperature swings during a load cycle. These temperature cycles can than be compared to published reliability data.
An FEM simulation has been used to calculate the thermal impedance for two modules.

Geometry with baseplate

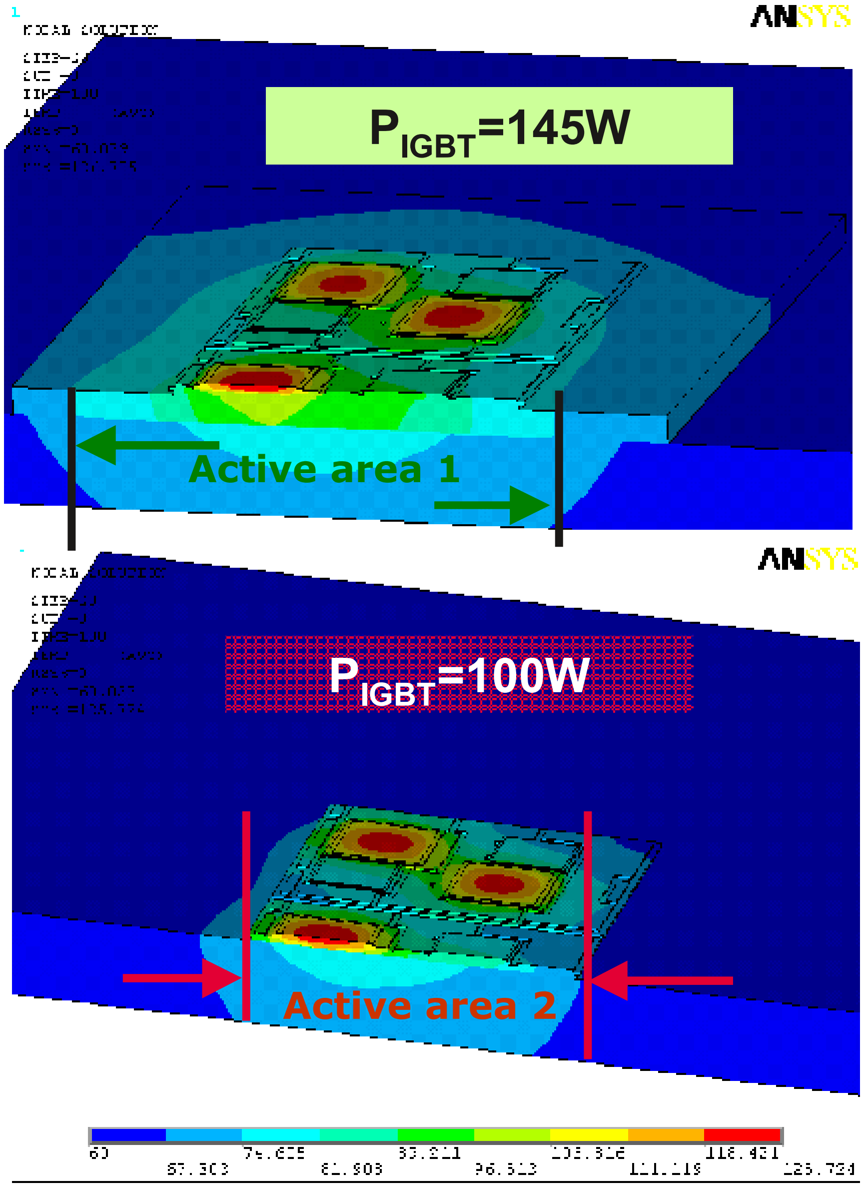


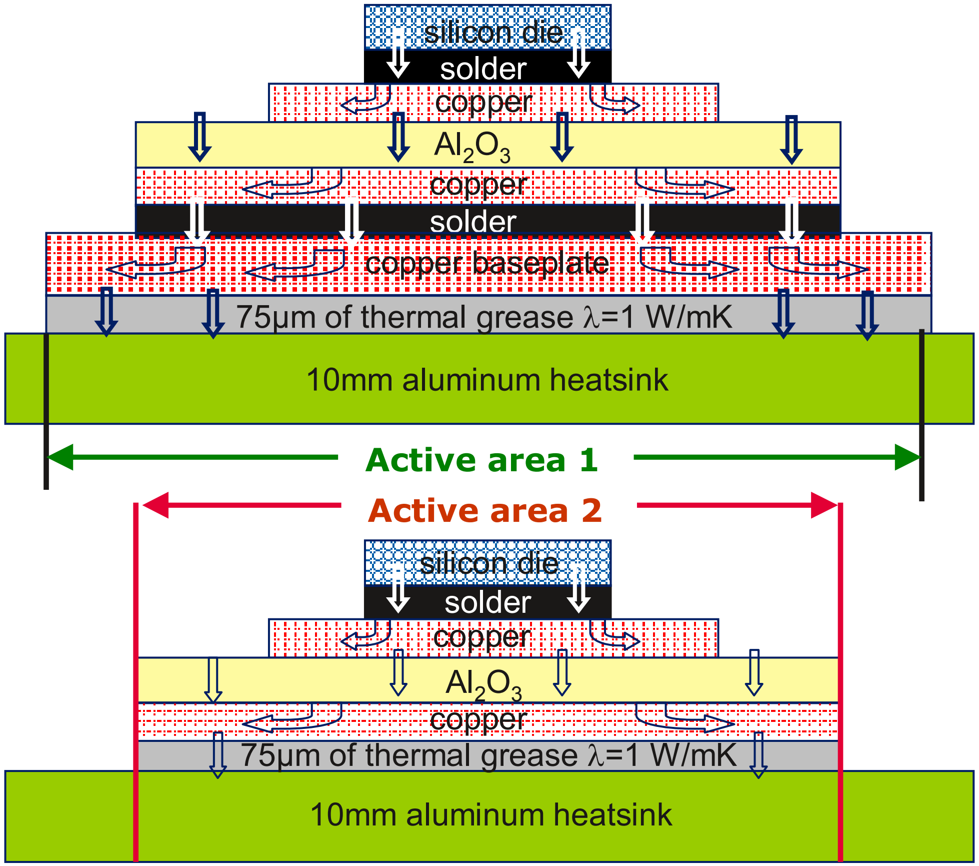
Geometry without baseplate



Silicon, DCB and cold plate as well as cooling conditions (defined as heat transfer of 1kW/m^{2}K for both systems) are the same for both modules.
T_A (meaning coolant temperature) is 60°C.

Why design a CAV module with a baseplate? The thermal stack up



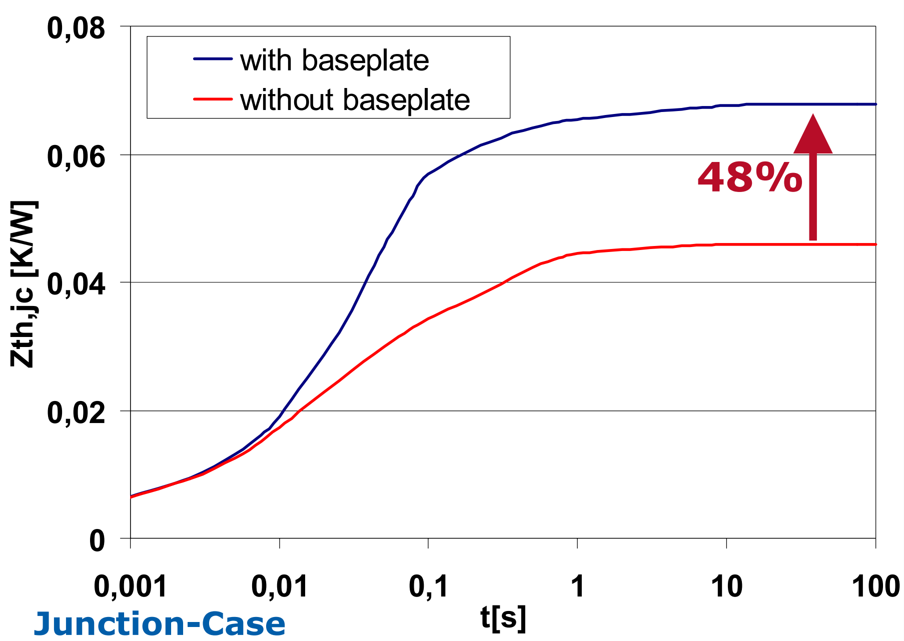


Geometry with baseplate

Geometry without baseplate

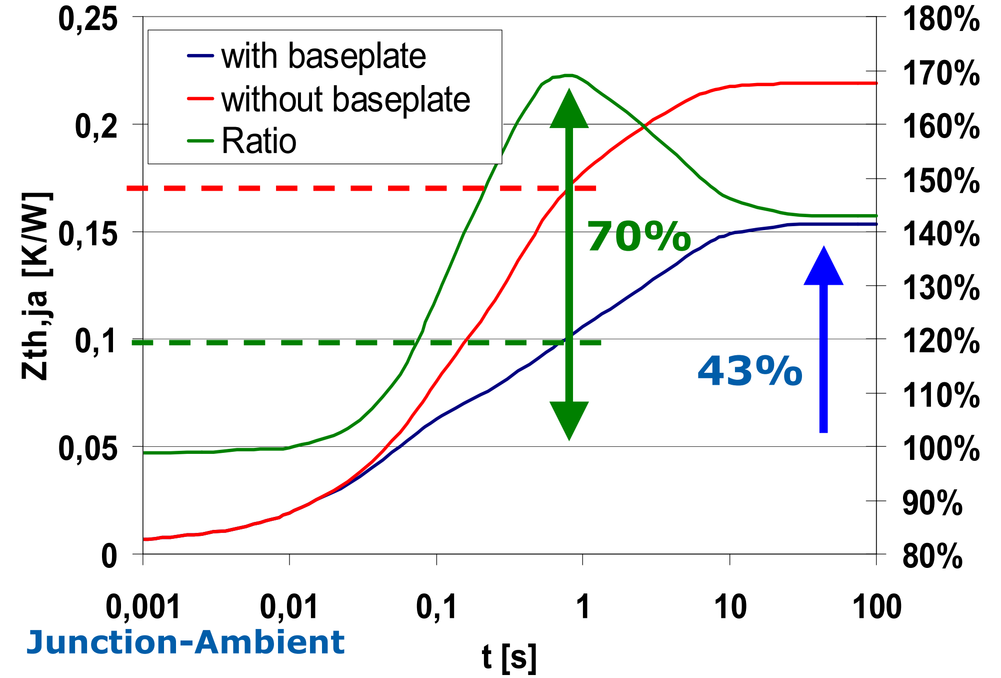
Baseplate enlarges active area of heat flow from module to heatsink. For the same T_J=125°C the module with a baseplate can dissipate 45% more power. This results in either more available inverter power or reduced junction temperatures.

Why design a CAV module with a baseplate? Thermal resistance and impedance (simulations)



Junction-Case

The thermal resistance from junction to case of a module with a baseplate is 48% greater than a baseplateless module (measured on DCB copper backside).



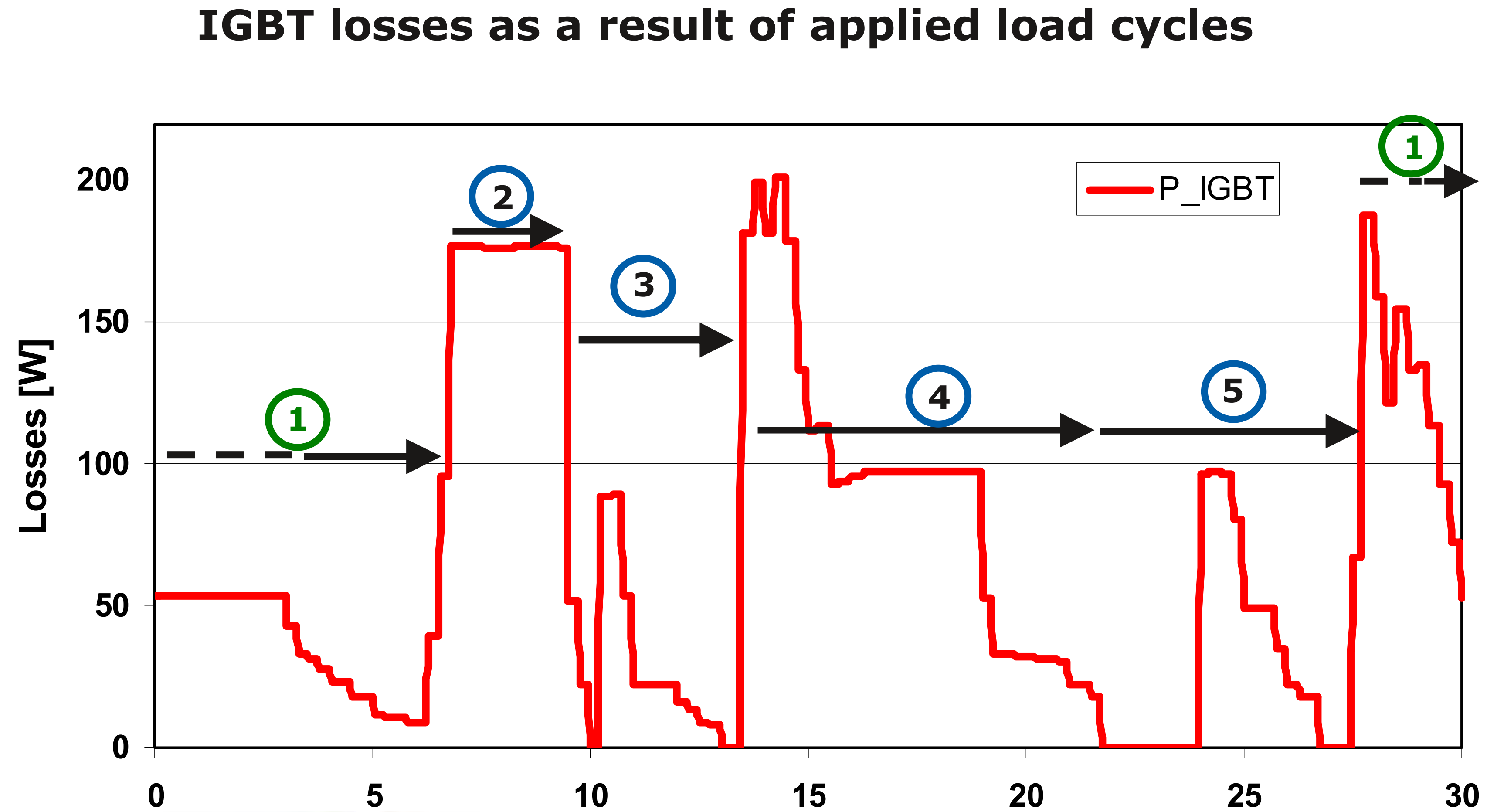
Junction-Ambient

The thermal impedance measured from junction to ambient, however, of module with a baseplate in better by 70% for a 1s time period and is 43% better in the steady state.

In reality only the thermal impedance from junction to ambient is important as silicon temperature is given by the thermal flow from silicon to ambient. In CAV applications the load is very dynamic and usually changes in time periods of seconds rather than minutes. The baseplate reduces the magnitude of the junction temperature swings under transient loads and hence increases the module lifetime.

Why design a CAV module with a baseplate?
Typical load profile (simulations)

IGBT losses as a result of applied load cycles

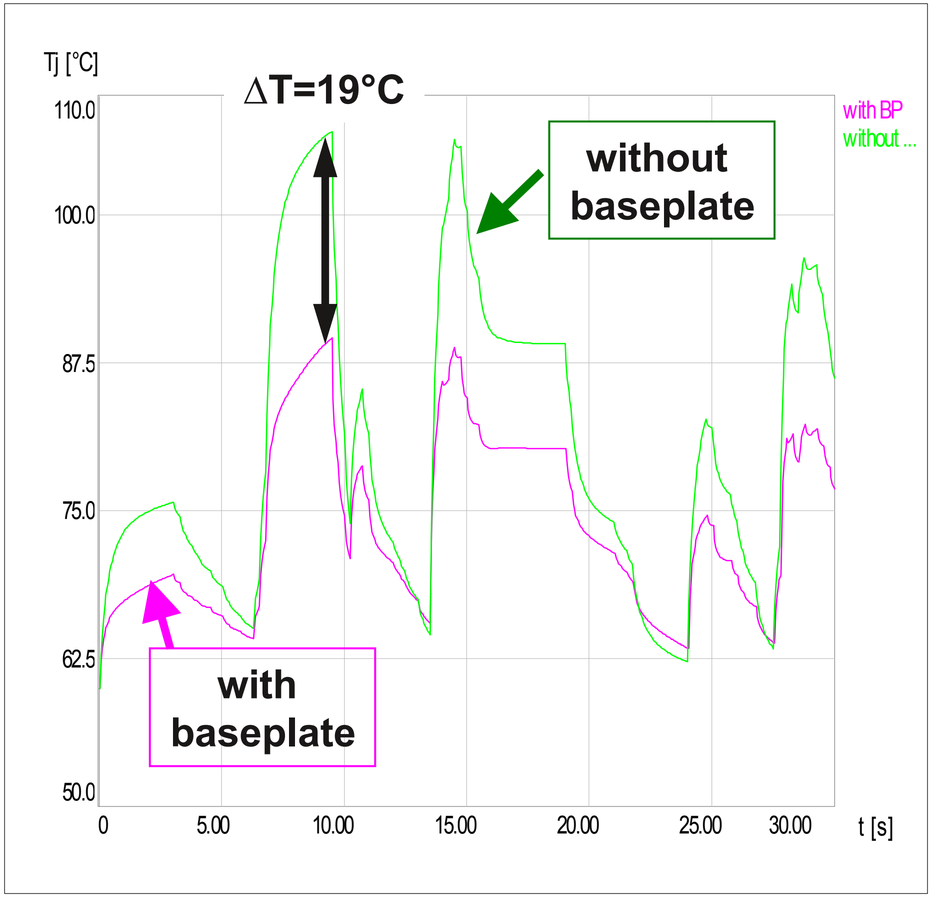


Source: Infineon System Engineering

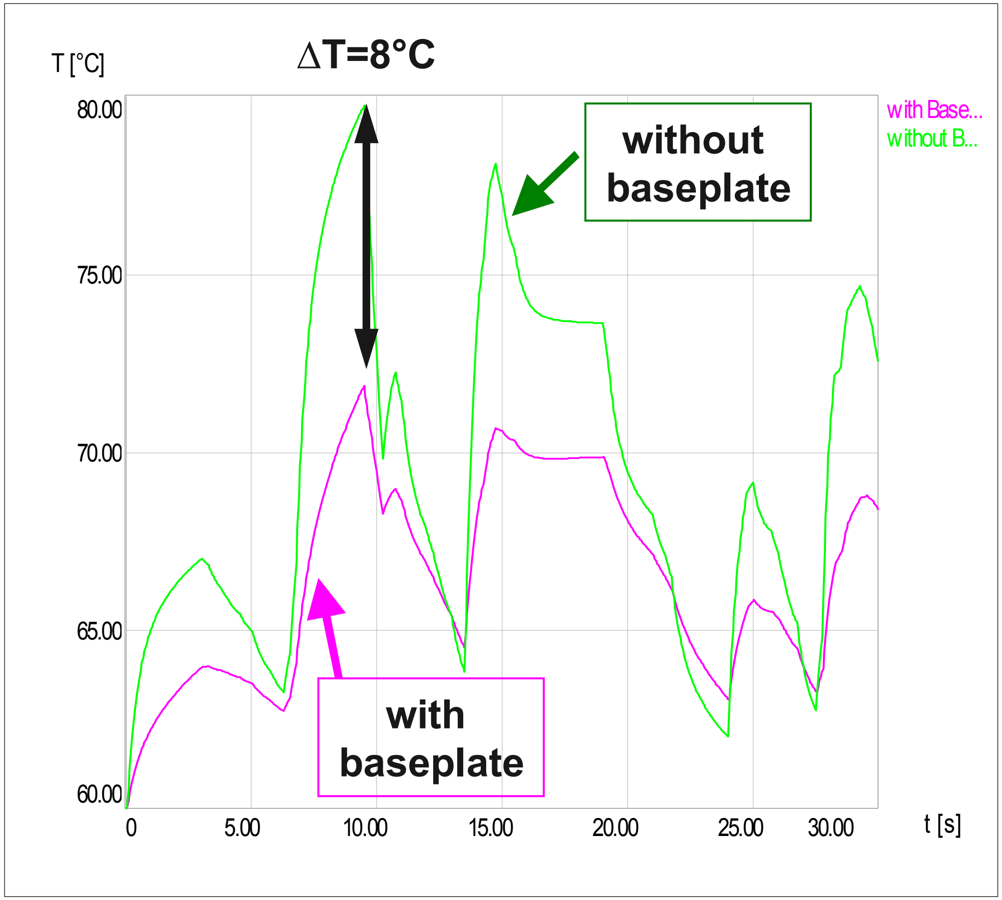
High dynamic load cycles are shorter than 5s

Why design a CAV module with a baseplate?
Typical load profile – influence on lifetime (simulations)

IGBT Junction Temperature



Solder and case temperature



Benefits of a module with baseplate vs. module w/o a baseplate for a given application:
-reduced junction temperature by 19°C results in an extra 19e6 power cycles
-reduced case temperature by 8°C results in available TC of >> 500 000 cycles

Result: longer lifetimes or same lifetime with a lower current rated module and /or increased inverter ratings.

CAV Power Module Portfolio by Application

Conclusions

Due to complex load cycles, the system and power semiconductor switches used in Commercial, Construction and Agriculture vehicles have higher reliability and environmental requirements than industrial and ‘typical’ automotive applications.

Appropriate module selection can be influenced by looking at the following facts:

- Baseplate design which increases module lifetimes due to superior thermal spreading
- Improved joining techniques – demonstrated by extremely high TC, TST and PC ratings
- Large product portfolio matching most CAV applications
- Long experience in transportation applications
- Source of semiconductor dies and module technology – the perfect synergy